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ORIGINALS ORIGINALARBEITEN

Compressive strength and stiffness of Radiata Pine laminated veneer lumber

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Abstract This paper describes results of experimental testing of compressive strength and stiffness of laminated veneer lumber (LVL) manufactured in New Zealand from Radiata Pine. It evaluates material properties of 45, 63 mm LVL and 36 mm crossbanded LVL in the three different material directions. Testing has been performed according to Australian/New Zealand Standards and European Standards. Results from experimental testing according to both standards are compared and a newly proposed method for strength increase due to stress spreading has been verified. Recommended design values for strength and stiffness are given.

Druckfestigkeit und Steifigkeit von Furnierschichtholz der Radiatakiefer

Zusammenfassung In dieser Arbeit werden die Ergebnisse der Druckfestigkeits- und Steifigkeitsprüfungen von Furnierschichtholz (LVL), das in Neuseeland aus Radiatakiefernholz hergestellt wurde, vorgestellt. Die Materialeigenschaften von 45, 63 mm LVL sowie von 36 mm LVL mit 2 Querlagen werden in den drei verschiedenen Materialrichtungen untersucht. Geprüft wurde gemäß australischen/neuseeländischen Normen sowie europäischen Normen. Die Ergebnisse der Prüfungen nach beiden Normen wurden verglichen und die Eignung eines kürzlich vorgeschlagenen Verfahrens zur Bestimmung der Druckfestigkeit quer zur Faserrichtung wurde bestätigt. Bemessungswerte für die Festigkeit und Steifigkeit werden empfohlen.

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1 Introduction

For engineering purposes timber can be regarded as an orthotropic material, which means that material properties vary depending upon the orientation. Being a naturally grown product, there are numerous factors which influence the strength and stiffness, resulting in significant variability of material properties. Laminated veneer lumber (LVL), made from rotary peeled veneers glued together using phenol resorcinol formaldehyde resin, has the advantage that defects are distributed, making the material properties relatively homogeneous compared to sawn timber (Buchanan 2007). Within LVL there is still variability caused by factors such as layer property manipulation, peeling methods, veneer thickness, densification and moisture content.

For LVL, three clearly defined material directions can be assigned, as there is no growth ring angle influence. These are shown in Fig. 1: (1) longitudinal—parallel to grain; (2) tangential—perpendicular to grain and parallel to glue lines; and (3) radial—perpendicular to grain and perpendicular to glue lines.

Several characteristic values of mechanical properties commonly used in engineering practice are supplied by New Zealand and Australian manufacturers (Carter Holt Harvey 2008; Nelson Pine Industries Limited 2010; Wesbeam 2005) as shown in Table 1. European LVL producer Metsä Wood (2009) supplies a much wider range of strength and stiffness values for their normal LVL (Kerto-S) and crossbanded LVL (Kerto-Q). New developments in the field of structural timber engineering, such as post-tensioned timber

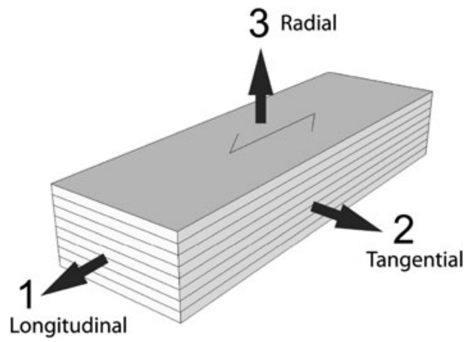


Fig. 1 LVL material directions
Abb. 1 Materialrichtung von Furnierschichtholz

construction (Buchanan et al. 2011; Palermo et al. 2005) with complex connection behaviour (van Beerschoten et al. 2011a, b), require more material properties than those provided by manufacturers in New Zealand and Australia. Furthermore, characteristic values are not always useful for research purposes, where average values and variations are of interest for evaluation of laboratory testing data.

Compressive behaviour of timber has been a topic of significant research (Hoffmeyer et al. 2000; Korin 1990; Thelandersson and Mårtensson 1997). In recent years compression perpendicular to grain has been the focus of publications (Blass and Görlacher 2004) due to changes in EN 1995-1-1:2004+AC+A1 (EC5, CEN 2004b). A theoretical explanation of bearing strength, based on the equilibrium method of plasticity, is presented by van der Put (2008) and it is claimed to accurately predict the compressive strength of different loading configurations (Leijten et al. 2010).

There have been several studies on mechanical properties of LVL, but many of these were targeting factors during the production process, such as applied pressure (Shukla and Kamdem 2008), layer composition (Burdulu et al. 2007) and different adhesives (Uysal 2005). Other research provided data comparing strength properties for different timber species (Aydin et al. 2004). Tensile strength perpendicular to grain of LVL was investigated by Ardalany et al. (2010). Furthermore a recent study (Franke and Quenneville 2010a) presented compression strength and stiffness values for solid New Zealand Radiata Pine and discussed the influence of different testing standards. Another publication by Franke and Quenneville (2010b) presented the material behaviour of Radiata Pine under compression which included LVL, but crossbanded LVL was not included and strength increase due to spreading of stresses was not further evaluated.

Worldwide there are several different testing standards to determine mechanical properties of timber. These standards use different test configurations and thus lead to different results (Leijten and Jorissen 2010). The experimental testing presented in this paper is focused on Radiata Pine LVL available on the Australian and New Zealand markets, and therefore testing was based on the joint Australian and New Zealand Standards AS/NZS 4357.2:2006 (2006a) and AS/NZS 4063.1:2010 (2010a). Testing has also been performed according to the European Standards EN 14374:2004 (CEN 2004a) and EN 408:2010 (CEN 2010) in order to compare different test configurations.

This paper describes experimental testing and analyses on the compressive strength and stiffness of New Zealand Radiata Pine LVL in three different material directions. It evaluates the properties of 45, 63 mm thick LVL and 36 mm thick crossbanded LVL. Strength results from different loading configurations are compared with predictions based on the model proposed by van der Put (2008) and by EC5 design procedures.

2 Experimental testing

2.1 Specimens

Testing was performed using five or six replicates (dependent on material availability) in the three different material directions for 45, 63 mm thick LVL and 36 mm

Table 1 Comparison of LVL characteristic compression strength (f_c) and stiffness (MOE) as specified by several manufacturers
Tab. 1 Vergleich der charakteristischen Druckfestigkeit (f_c) und des E-Moduls (MOE) von Furnierschichtholz gemäß der Angaben verschiedener Hersteller

Material	Timber species	$f_{c,1}$	$f_{c,2}$	$f_{c,3}$	MOE_1^a	MOE_2	MOE_3
Nelson Pine LVL11	Radiata Pine	45	12	–	11,000	–	–
Nelson Pine crossbanded LVL	Radiata Pine	No values specified					
Carter Holt Harvey hySPAN	Radiata Pine	45	12	–	13,200	–	–
Wesbeam e-beam E13	Maritime Pine	47	12	–	13,200	–	–
Kerto-S (parallel)	Spruce	35	6.0	1.8	13,800	430	130
Kerto-Q (crossbanded)	Spruce	26	9.0	2.2	10,500	2,400	130

All values in MPa

[a] Characteristic values for MOE_1 are based on four-point bending tests

Table 2 Specimen description and dimensions
Tab. 2 Bezeichnung und Abmessungen der Prüfkörper

Load direction	Material	Standard	Name	No. of tests	Length (mm)	Depth (mm)	Height (mm)
Longitudinal	LVL11 (45 mm)	NZS4357	E1-NZS-45	6	45	45	270
	LVL11 (63 mm)	NZS4357	E1-NZS-63	5	63	63	378
	Crossbanded	NZS4357	E1-NZS-CB	6	36	36	216
Tangential	LVL11 (45 mm)	NZS4063	E2-NZS-45	6	270	45	45
		EN408	E2-EN-45	5	70	45	90
	LVL11 (63 mm)	NZS4063	E2-NZS-63	5	378	63	63
		EN408	E2-EN-63	5	70	63	90
	Crossbanded	NZS4063	E2-NZS-CB	6	216	36	36
		EN408	E2-EN-CB	5	70	36	90
Radial	LVL11 (45 mm)	NZS4063	E3-NZS-45	6	270	45	45
		EN408	E3-EN-45	5	70	45	90
	LVL11 (63 mm)	NZS4063	E3-NZS-63	5	378	63	63
		EN408	E3-EN-63	5	70	63	126
	Crossbanded	NZS4063	E3-NZS-CB	6	216	36	36
		EN408	E3-EN-CB	5	70	36	98

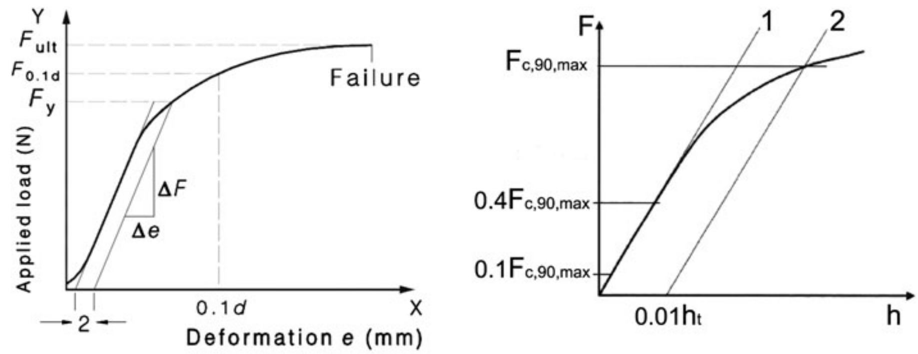
thick crossbanded (CB) LVL (having two out of ten veneers as cross-layers) according to Australian/New Zealand and European Standards. Specimens were taken from LVL11 and cross-banded LVL manufactured by Nelson Pine Ltd. LVL11 has been chosen as all manufacturers in Australia and New Zealand can supply this material. Specimens were labelled as Direction Standard Material Number, i.e. E1-EN-45-1 for testing in the longitudinal direction, according to the European Standard for 45 mm LVL of specimen Number 1. Specimen dimensions were as close as possible to values described in the standards, but because of material dimensions, not all dimensional requirements could be fulfilled. In total, 81 specimens were tested with dimensions as shown in Table 2. Density of specimens ranged between 575 and 588 kg/m^3 with an average of 581 kg/m^3. This was slightly above the average published density of 570 kg/m^3 for Nelson Pine LVL11.

2.2 Testing standards

The AS/NZS 4357.2:2006 (2006a) was used for testing of strength and stiffness parallel to grain, but this standard does not provide any test methods for properties perpendicular to grain. Therefore the rail test in Appendix A3 of AS/NZS 4063.1:2010 (2010a) was also used. In this test only the mid-section of the specimen is loaded and strength increase due to spreading of stresses can take place. Maximum strength values are the lesser of F_{ult} and $F_{0.1d}$, where the latter is based on a constant '0.1 $\times$ d' (d = depth of cross-section in mm) offset intercept as shown in Fig. 2a. The stiffness is based on a linear deformation offset of 2 mm, regardless of specimen size. The intersection of this offset with the load-displacement curve gives the yield strength. No specification is given for derivation of the slope (stiffness) of the load-displacement curve. Therefore the measurements at 10 and 40 % of yield strength have been used to evaluate stiffness, similar to the method of the European Standard.

European Standards have also been used for compression testing. EN 14374:2004 (CEN 2004a) specifies requirements for LVL, although for testing it refers to methods outlined in EN 408:2010 (CEN 2010). For parallel to grain strength and stiffness the standard is identical to the New Zealand Standard, therefore these tests were not repeated. For compression perpendicular to grain a block compression test is specified. Maximum strength is based on the intersection of the load-deformation curve with a '0.01 $\times$ h' (h = height of specimen in mm) linear offset from the initial stiffness, as is illustrated in Fig. 2b. The initial stiffness is defined as the slope of the load-deformation curve between 10 and 40 % of the maximum load.

Statistical analysis of the AS/NZS testing has been performed according to AS/NZS 4357.3:2006 (2006b) and AS/NZS 4063.2:2010 (2010b), where a log-normal distribution of the test results has been assumed and statistical evaluation Method 1 (Appendix B2.2) from the standard has been followed. It should be noted that the standard assumes a sample size of 30 or more, which is not the case for this work. Statistical analysis according to European Standard EN 14358:2006 (CEN 2006) has been performed in order to calculate characteristic values for wood-based



(a) AS/NZS4063 (b) EN408

Fig. 2 Derivation of strength and stiffness based on AS/NZS 4063 and EN 408
Abb. 2 Bestimmung der Festigkeit und Steifigkeit nach AS/NZS 4063 und EN 408

products, based on an assumed logarithmic normal distribution. Both evaluation methods are very similar, though the Australian/New Zealand Standard specifies a minimum coefficient of variation of 10 %, whereas the European Standard specifies a minimum of 5 %.

A limitation of this work is that it is based on one batch of LVL from one manufacturer. AS/NZS 4063.2:2010 requires a minimal sample size of 30 specimens for determination of characteristic values. Therefore values published in this paper should not be used directly for design purposes, but they do give an indication for preliminary design and research purposes. Timber manufacturers should perform similar testing on larger sample sizes in order to supply design characteristic values.

2.3 Test setup

The compression testing was performed using an Instron testing frame with an in-line 150 kN load cell. A linear displacement potentiometer (50 mm travel) was attached to measure crosshead movement, required for the AS/NZS testing. Two small linear displacement potentiometers (10 mm travel) were attached to specimens tested to the EN Standard. These potentiometers were fixed to nails which were placed at 20 and 80 % of the specimen height. Testing was stopped at 10 % strain deformation, as further deformation was deemed unrealistic.

2.4 Failure mechanisms

Failure mechanisms were relatively consistent among groups of test specimens and can be seen in Fig. 3. Longitudinally loaded specimens (Fig. 3a) generally started to fail in compression, after which they buckled to one side. Tangentially loaded block specimens (Fig. 3b) failed due to crushing, whereby sometimes the outer veneers peeled off. Radially loaded block specimens (Fig. 3c) showed a high amount of crushing, with some of the layers crushing significantly more than others. Tangentially loaded rail specimens (Fig. 3d) failed when the specimen started bulging outwards and outer veneers peeled off. Radially loaded rail specimens (Fig. 3e) started failing around the edges of the load block and eventually tensile failure at the ends occurred.

3 Compression strength results

Table 3 shows the average strength, coefficient of variation, fifth percentile and characteristic strength values for the two different test setups for the three different materials and in the three different orientations.

As expected, a clear distinction between parallel ($f_{c,1}$) and perpendicular ($f_{c,2}$ and $f_{c,3}$) to grain strength was observed. Perpendicular to grain strength of 45 and 63 mm LVL showed a small reduction in strength for radially loaded specimens ($f_{c,3}$) compared to tangentially loaded ones ($f_{c,2}$). This was most likely due to all veneers sharing the load under tangentially loading, but under radial loading there was no load sharing and the weakest veneers governed strength.

It can be seen that 45 and 63 mm LVL had a low variability, ranging between 2.5 and 5.4 %. 36 mm crossbanded LVL had a slightly higher variability, up to 9.4 %. It should be kept in mind that this was only the variability within one batch of LVL and does not represent the variability between different batches.

When comparing 45 and 63 mm LVL, reasonably similar strength values for all three directions were found. Crossbanded LVL is made from lower grade veneers, which manifested in a reduced compression strength parallel to grain ($f_{c,1}$) which was almost half compared to the other types of LVL. The two cross layers significantly increased the tangential strength ($f_{c,2}$). The compressive strength in the radial direction ($f_{c,3}$) was similar to other types of LVL.

When comparing the compressive strength of EN test results with the AS/NZS test results, it can be seen that the compressive strength parallel to grain was the same

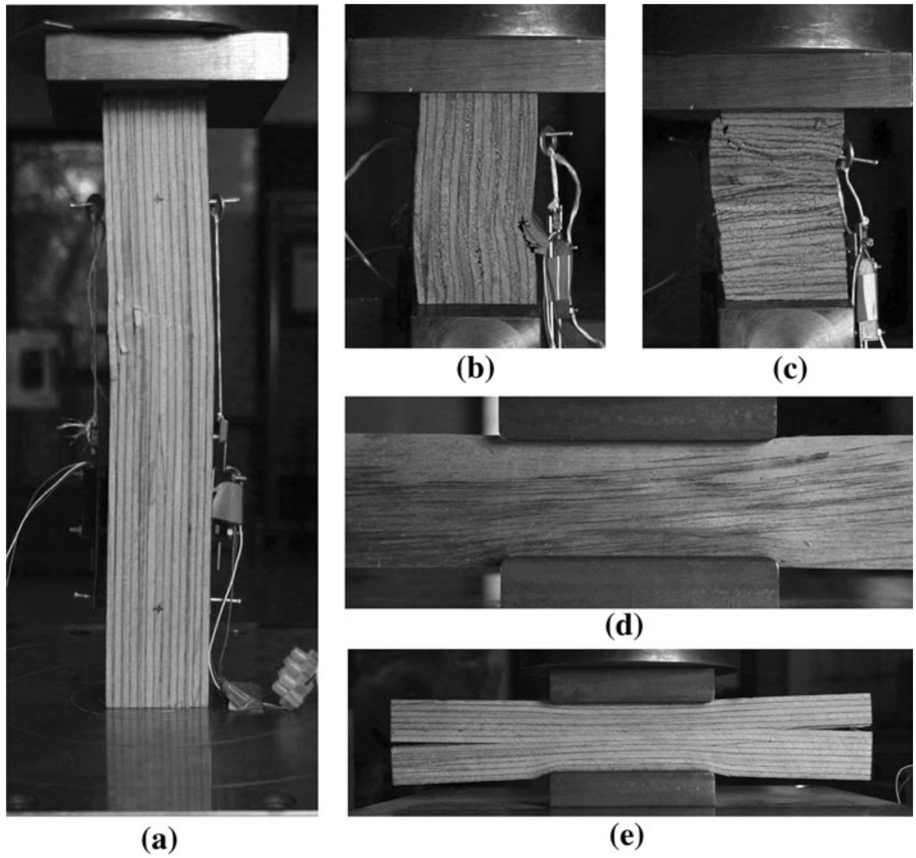


Fig. 3 Typical failures of **a** longitudinally loaded specimen, E1-NZS; **b** tangentially loaded block specimen, E2-EN; **c** radially loaded block specimen, E3-EN; **d** tangentially loaded rail specimen, E2-NZS; **e** radially loaded rail specimen, E3-NZS

Abb. 3 Typische Bruchbilder **a** eines in Längsrichtung beanspruchten Prüfkörpers, E1-NZS; **b** eines tangential beanspruchten Blockprüfkörpers, E2-EN; **c** eines radial beanspruchten Blockprüfkörpers, E3-EN; **d** einer tangential beanspruchten Schwelle, E2-NZS; **e** einer radial beanspruchten Schwelle E3-NZS

Table 3 Compression test results including average strength ($\bar{f}$), coefficient of variation (CoV), fifth percentile (f_{05}) and characteristic strength (f_k) values (MPa) for the different materials, orientations and testing standards

Tab. 3 Ergebnisse der Druckprüfung: mittlere Festigkeit ($\bar{f}$), Variationskoeffizient (CoV), 5 % Quantilwerte (f_{05}) und charakteristische Festigkeitswerte (f_k) (MPa) in Abhängigkeit der verschiedenen Materialien, Prüfrichtungen und Prüfnormen

Standard	Result	45 mm LVL			63 mm LVL			36 mm CB LVL		
		$f_{c,1}$	$f_{c,2}$	$f_{c,3}$	$f_{c,1}$	$f_{c,2}$	$f_{c,3}$	$f_{c,1}$	$f_{c,2}$	$f_{c,3}$
AS/NZS	$\bar{f}$ (MPa)	47.4	13.4	10.0	47.8	15.2	12.3	25.3	19.1	10.6
	CoV (%)	4.1	5.0	3.9	4.8	3.5	5.0	4.4	9.4	5.8
	f_{05} (MPa)	44.3			44.1			23.6		
	f_k (MPa)	42.2	13.1	9.7	41.8	14.7	11.9	22.4	18.6	10.3
EN	$\bar{f}$ (MPa)	47.4	8.2	7.5	47.8	9.1	7.9	25.3	16.8	7.3
	CoV (%)	4.1	4.1	5.4	4.8	2.5	2.7	4.4	3.1	5.7
	f_k (MPa)	42.0	7.3	6.6	42.2	8.1	7.0	22.5	14.9	6.3

because both standards specify the same test setup and therefore the testing was performed only once. There is a minor difference in characteristic strength, due to differences in the statistical analysis procedure. For analysis of tangential and radial strength of the AS/NZS testing a fixed '0.1 × h' deformation offset based on crosshead movement was used, whereas for the EN testing a 1 % strain offset, based on the average of two potentiometers, parallel to the initial stiffness was used, as shown in Fig. 2b. The different measurements and analysis procedures made for an unequal comparison. In general a clear reduction in compressive strength perpendicular to grain can be seen (both tangential and radial) as sideways spreading of stresses was not possible in the block test.

4 Stress spreading

It is not practical to give different strength values for every possible loading scenario. Therefore predictive methods

are necessary in order to predict compressive strength under different loading scenarios.

Van der Put (2008) proposes a theoretical model to take strength increase due to stress spreading into account based on the equilibrium method of plasticity. This method leads to Eq. 1 for the calculation of compressive strength perpendicular to grain when spreading of stresses can take place ($f_{c,s}$). This function can be rewritten to find the increase in strength due to stress spreading (k_c), as is given by Eq. 2.

$$f_{c,s} = f_{c,90}\sqrt{\frac{L}{s}} \tag{1}$$

$$k_c = \frac{f_{c,s}}{f_{c,90}} = \sqrt{\frac{L}{s}} \tag{2}$$

Where:

$f_{c,90}$	Block compressive strength
$f_{c,s}$	Compressive strength incl. spreading effects
L	Effective length
s	Contact length in the grain direction
k_c	Factor for increase in strength due to stress spreading

A stress dispersion angle of 1:1 is suggested for elastic stress distribution, at small strains or at servicability limit state (SLS) conditions, and the maximum spreading angle at higher strains, or ultimate limit state (ULS) conditions, 1:1.5. This leads to an effective length for rail tests of $L_{eff,sls} = L + h$ and $L_{eff,uls} = L + 1.5\,h$, as shown in Fig. 4. The distinction in compressive strength at SLS and ULS limit was previously proposed by Thelandersson and Mårtensson (1997) and Gehri (1997).

Another model to take different loading scenarios into account is currently in EC5 (CEN 2004b) in the section for design of compression perpendicular to grain. This design procedure is based on a block compressive strength ($f_{c,90,d}$) multiplied by a factor ($k_{c,90}$) which depends on the loading configuration and type of timber. This is shown in Eq. 3. Furthermore the design stress is based on effective area

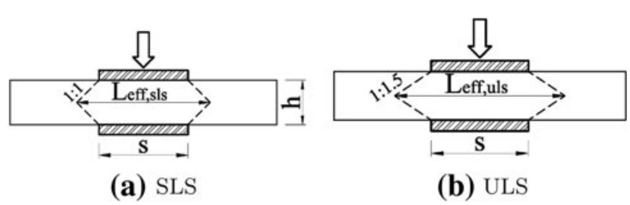


Fig. 4 Stress dispersion angles for testing according to AS/NZS 4063.1:2010 in SLS and ULS conditions

Abb. 4 Spannungsausbreitungswinkel bei der Prüfung gemäß AS/NZS 4063.1:2010 unter SLS und ULS Bedingungen

(A_{ef}) which increases the contact length, as is shown in Eq. 4.

$$\sigma_{c,90,d} \le k_{c,90} f_{c,90,d} \tag{3}$$

$$\sigma_{c,90,d} = \frac{F_{c,90,d}}{A_{ef}} \tag{4}$$

Where:

$f_{c,90,d}$	Block compressive strength
$k_{c,90}$	Factor based on loading configuration and type of timber
$\sigma_{c,90,d}$	Design compressive stress
$F_{c,90,d}$	Design compressive force
A_{ef}	Effective contact area

Metsä Wood (2009) has published design information for their Kerto LVL products, as EC5 only gives values for solid timber and glue-laminated timber. In this document, several values for the increase in contact length and $k_{c,90}$ factor are given, depending on the material and loading orientation. These values are shown in Table 4. Kerto-S has all laminates in one direction whereas Kerto-Q is crossbanded LVL.

Table 5 shows compressive strength ratios of rail test over the block test. This ratio has been analysed for three types of LVL at SLS and ULS design limits. Compressive strength tangentially ($f_{c,2}$) and radially ($f_{c,3}$) have been evaluated separately. A total of three ratios are shown for each material; one based on experimental testing, one based on the van der Put model and one based on EC5 design rules.

For experimental testing, SLS stresses have been evaluated based on the 1 % offset method, as outlined in EN 408:2010 (CEN 2010). ULS stresses have been taken as the highest of the maximum stress during testing or the stress at 10 % strain, based on AS/NZS 4063.1:2010 (2010a). All values are average strength values based on strain measurement using the crosshead displacement. The full stress vs. strain curves for tangential loading are shown in Fig. 5. From these graphs it can be seen that rail tests result in higher strengths compared to block tests for 45 and 63 mm LVL but not for crossbanded LVL. It can also be seen that even at 10 % strain the rail test strength is still increasing, whereas the block test reaches a maximum strength around 7 % strain.

Also shown in Table 5 are the effective length and k_c-factor according to the van der Put model. Furthermore, the effective length and increase in strength ratio based on EC5 and the Kerto design information are included. The EC5 factor is a multiplication of $k_{c,90}$ factor and effective length over contact length. These two factors are both predictions of the increase in strength of the rail test in comparison to the block test. These values can therefore be compared with the experimental ratio.

It can be seen that the van der Put model gives excellent results for the compressive strength perpendicular to grain (E2) of 45 mm LVL at SLS and ULS levels. It also gives good results for 63 mm LVL. Radially loaded (E3) specimens showed a very small amount of stress spreading (6 and 5 %) for 45 mm LVL. For 63 mm LVL there was some spreading of stresses (18 and 26 %), but less than perpendicular to grain. This suggests stress spreading should not (or only partially) be taken into account for radially loaded specimens.

Table 4 Contact length and $k_{c,90}$ factor for Kerto LVL (Metsä Wood 2009)
Tab. 4 Kontaktlänge und $k_{c,90}$ Faktor von Kerto Furnierschichtholz (Metsä Wood 2009)

Material	Increase of contact length	$k_{c,90}$-continuous supports
Kerto-S, edgewise	30 mm along	1.0
Kerto-S, flatwise	30 mm along 15 mm across	1.4
Kerto-Q, edgewise	0 mm along	1.3
Kerto-Q, flatwise	30 mm along 15 mm across	1.4

edgewise = tangential, flatwise = radial

Crossbanded LVL had almost no increase in strength in the rail test compared to the block test in SLS or in ULS (1 and 4 %, respectively). Therefore spreading of stresses should not be included in the design of crossbanded LVL. Some stress spreading occurred in the radial direction, but this was still less than predicted by the van der Put model.

The effective length based on EC5 strongly overestimated the compressive strength of all rail specimens as tested according to AS/NZS standards. Also the $k_{c,90}$ factors as specified for Kerto LVL do not match up with experimental results. Therefore this design method is not able to predict the compressive strength of New Zealand Radiata Pine LVL.

5 Compression stiffness results

The average, 5th percentile and characteristic stiffness values are shown in Table 6 in the three material

Table 5 Comparison of experimental and predicted (van der Put model 2008 and Eurocode 5 2004b) compressive strength ratios for LVL at SLS and ULS design limits
Tab. 5 Vergleich der experimentell bestimmten und der nach dem van der Put Modell (2008) vorhergesagten und dem mit Eurocode 5 (2004b) berechneten Spannungserhöhungsfaktoren für LVL für die Bemessungsfälle SLS und ULS

Design limit	Method	45 mm LVL		63 mm LVL		36 mm CB LVL	
		$f_{c,2}$	$f_{c,3}$	$f_{c,2}$	$f_{c,3}$	$f_{c,2}$	$f_{c,3}$
SLS	Experimental						
	Block (EN) (MPa)	8.7	7.8	9.7	7.9	17.6	7.5
	Rail (AS/NZS) (MPa)	10.6	8.2	11.8	9.3	17.8	8.3
	ratio (rail/block)	*1.23*	*1.06*	*1.21*	*1.18*	*1.01*	*1.10*
	van der Put						
	l_{eff} (mm)	135	135	153	153	126	126
	$k_c - factor$	*1.22*	*1.22*	*1.30*	*1.30*	*1.18*	*1.18*
	EC5 & Kerto						
	l_{eff} (mm)	150	150	150	150	90	150
	$k_{c,90}$	1.0	1.4	1.0	1.4	1.3	1.4
	EC5-factor $k_{c,90} \times (l_{eff}/l)$	*1.67*	*2.33*	*1.67*	*2.33*	*1.30*	*2.33*
ULS	Experimental						
	Block (EN) (MPa)	10.2	9.5	11.4	9.7	18.4	9.0
	Rail (AS/NZS) (MPa)	13.4	10.0	15.2	12.3	19.1	10.6
	ratio (rail/block)	*1.32*	*1.05*	*1.33*	*1.26*	*1.04*	*1.18*
	van der Put						
	l_{eff} (mm)	157.5	157.5	184.5	184.5	144	144
	$k_c - factor$	*1.32*	*1.32*	*1.43*	*1.43*	*1.27*	*1.27*
	EC5 & Kerto						
	l_{eff} (mm)	150	150	150	150	90	150
	$k_{c,90}$	1.0	1.4	1.0	1.4	1.3	1.4
	EC5-factor $k_{c,90} \times (l_{eff}/l)$	*1.67*	*2.33*	*1.67*	*2.33*	*1.30*	*2.33*

Italic values show compressive strength increase of rail test compared to block test

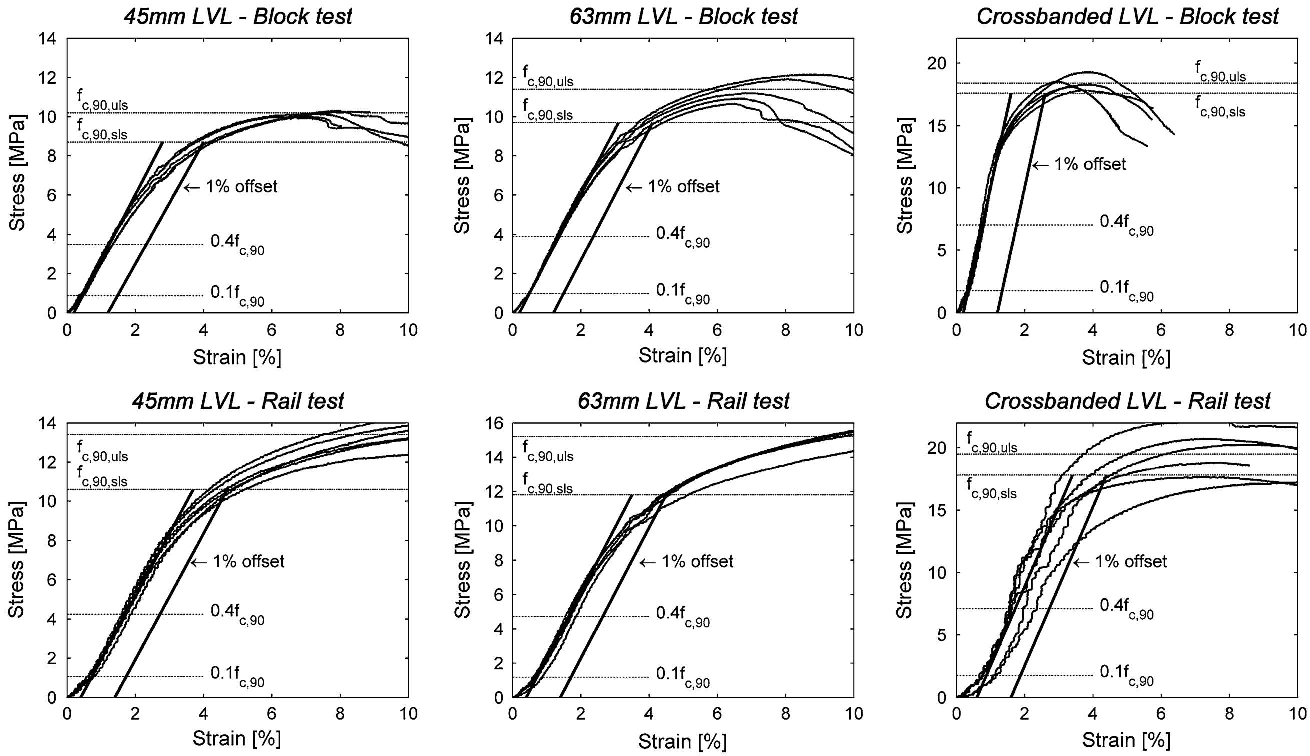


Fig. 5 Stress-strain plots for compressive block and rail tests loaded in tangential direction

Abb. 5 Spannungs-Dehnungs-Diagramme für Block- und Schwellendruckprüfungen bei Beanspruchung in tangentialer Richtung

Table 6 Experimental compressive stiffness results including average ($\overline{E}$), coefficient of variation (CoV), fifth percentile (E_{05}) and characteristic stiffness ($E_{k,mean}$) values (MPa) based on AS/NZS 4063.2:2010 and EN 14358:2006

Tab. 6 Ergebnisse der experimentell bestimmten Drucksteifigkeit: mittlerer E-Modul ($\overline{E}$), Variationskoeffizient (CoV), 5 % Quantilwert (E_{05}) und charakteristische Steifigkeit ($E_{k,mean}$) (MPa) gemäß AS/NZS 4063.2:2010 und EN 14358:2006

Standard	Test	45 mm LVL			63 mm LVL			36 mm CB LVL		
		E1	*E2*	*E3*	*E1*	*E2*	*E3*	*E1*	*E2*	*E3*
AS/NZS	$\overline{E}$ (MPa)	12,200	319	241	12,500	379	371	8,370	622	361
	CoV (%)	7.3	4.4	6.3	1.7	2.7	5.7	13.3	16.3	6.0
	E_{05} (MPa)	10,800	297	217	12,200	362	337	6,670	470	327
	$E_{k,mean}$ (MPa)	12,100	328	243	13,200	394	374	8,050	585	365
EN	$\overline{E}$ (MPa)	12,200	426	371	12,500	527	541	8,370	2,460	564
	CoV (%)	7.3	5.0	8.6	1.7	11.7	15.9	13.2	9.6	7.2
	E_{05} (MPa)	10,800	392	321	12,200	432	411	6,670	2,090	499

orientations for the three different materials. A differentiation is made between rail testing according to AS/NZS and block testing according to the EN Standard. The statistical analysis of test data has been performed according to AS/NZS 4357.3:2006 (2006b) and AS/NZS 4063.2:2010 (2010b). A log-normal distribution of the test results has been assumed and Appendices B3 and B5 from the standard have been followed.

The stiffness values parallel to grain were much higher than stiffness perpendicular to grain. The tangential stiffness (E2) was slightly higher than the radial stiffness (E3). This was most likely due to stiffer and weaker layers sharing the load perpendicular to grain, whereas the weakest layers are governing the stiffness in the radial direction. Gluelines are not expected to influence stiffness in tangential direction due to the brittle nature of the glue and the very small volume ratio of glue to veneers. Stiffness values of 45 and 63 mm LVL exhibited some differences, but for design practice they can be assumed to be the same. Crossbanded LVL had a lower stiffness parallel to grain (E1) than the other materials, but an increase in stiffness perpendicular to grain (E2), as would be expected

from the cross-layers. The variability in stiffness of crossbanded LVL (E1 and E2) was almost twice that of 45 and 63 mm LVL.

Stiffness perpendicular to grain (E2 and E3) for the EN block tests were on average 1.4 times higher as stiffness based on AS/NZS rail tests for 45 and 63 mm LVL. The stiffness perpendicular to grain (E2) of crossbanded LVL was four times higher for the block test compared to the rail test. These seemingly contradictory results were likely due to differences in methods of measuring displacements. The results of the AS/NZS tests were calculated from crosshead movement, whereas results of the EN testing were based on potentiometers attached to the sides of specimens. Previous research concluded that modulus of elasticity strongly depends on gauge length. Hoffmeyer et al. (2000) found that crosshead movement gives a stiffness value of only 69 % (structural timber) to 75 % (glulam) compared to stiffness values based on 50 or 100 mm gauge length extensometers. For EN testing, a ratio of 70 % was found for average stiffness of 45 and 63 mm thick LVL when comparing strains based on crosshead movement with strains based on the potentiometers.

6 Design values

Compression testing showed only minor variations in properties between 45 and 63 mm LVL, therefore for design purposes these materials can be considered identical. An overview of recommended design values is given in Table 7.

The calculated characteristic strength of LVL parallel to grain of 42 MPa is lower than the specified characteristic compressive strength of 45 MPa, but that is possibly due to the small sample size. The experimental 5th percentile strength of 44 MPa corresponds well with the specified value of 45 MPa. For tangential to grain strength ($f_{c,2}$), the manufacturers specified value of 12 MPa is only valid for small connections with a similar configuration to the rail test, where stress spreading can take place and plastic deformations are allowed. A better design approach is to use a compressive strength of 8 MPa for SLS design, based on the characteristic strength of EN block testing. At this level material behaviour is still largely linear elastic. For ULS design a value of 10 MPa can be used if plastic deformation is accepted. For radial load ($f_{c,3}$) a design strength of 7 MPa can be used, based on the characteristic strength value of EN block testing. If plastic deformation of the timber is allowed, this value can be increased to 9 MPa.

When having different loading configurations than pure compression, an increase in compression strength due to spreading of stresses can be taken into account. This can be done using the proposed plasticity model of van der Put (2008). Stress spreading is only occurring for compression in the tangential direction, for radial direction stress spreading should not be allowed for.

Based on experimental testing of crossbanded LVL, the recommended design strength parallel to grain is 24 MPa. Perpendicular to grain, a compressive strength of 16 MPa for linear elastic behaviour and 18 MPa for plastic behaviour are suggested. No stress spreading should be allowed for crossbanded LVL.

Recommended compressive stiffness for 45 and 63 mm LVL parallel to grain is the average experimental result of 12,000 MPa. This is slightly higher compared with the 11,000 MPa value specified by the manufacturer, which is based on a four-point bending test and includes some shear deformation. Stiffness perpendicular to grain (E2, tangentially) should be based on average values from EN testing and can be taken as 500 MPa. Stiffness in the radial direction (E3) is very similar to tangentially and can therefore also be taken as 500 MPa. Suggested stiffness values for crossbanded LVL are 8,400 MPa parallel to grain (E1), 2,500 MPa perpendicular to grain (E2) and in the radial direction (E3) 500 MPa.

7 Conclusion

Experimental testing of Radiata Pine LVL manufactured in New Zealand has resulted in a greater understanding of the material behaviour under compression. Strength and stiffness in three material directions have been evaluated. Testing has been performed based on rail tests as specified by the Australian/New Zealand Standards and block tests according to the European Standards. The rail test, as specified by the Australian and New Zealand Standard (AS/NZS 4063.1:2010), does not give appropriate strength and stiffness values as stress spreading influences the results.

Table 7 Recommended preliminary design values
Tab. 7 Empfohlene vorläufige Bemessungswerte

	$f_{c,1}$	$f_{c,2,sls}$	$f_{c,2,uls}$	$f_{c,3,sls}$	$f_{c,3,uls}$	$E1$	$E2$	$E3$
45 mm/63 mm LVL	44	8	10	7[a]	9[a]	12,000	500	500
36 mm crossbanded LVL	24	16[a]	18[a]	7[a]	9[a]	8,400	2,500	500

[a] No stress spreading allowed

Therefore recommended strength and stiffness values based on the European test method (EN 14374:2004 and EN 408:2010) are given.

A design strength of 44 MPa parallel to grain compares well with the 45 MPa specified by manufacturers. The compressive strength perpendicular to grain of 12 MPa is only reached under specific loading conditions. A better approach is to use a compressive strength of 8 MPa under uniform compression with small deformations and 10 MPa when plastic deformation is acceptable.

The plasticity model of van der Put provides a good prediction of strength increase under different loading configurations due to spreading of perpendicular to grain stresses. This method can be used for design at SLS and ULS for tangential loads, but care should be taken for radial loading as spreading of stresses cannot be fully relied on. Crossbanded LVL hardly experiences any spreading of stresses and this should not be allowed for in design.

Although this paper gives recommendations for design values, these are based on limited numbers of tests on one batch of LVL. Manufacturers should consider performing additional testing to supply design values for their different LVL products.

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References

Ardalany M, Deam B, Fragiacomo M, Crews K (2010) Tension perpendicular to grain strength of wood, laminated veneer lumber (LVL), and cross-banded LVL (LVL-C). In: 21st Australasian conference on the mechanics of structures and materials, Melbourne

Aydin I, Çolak S, Çolako lu G, Salih E (2004) A comparative study on some physical and mechanical properties of laminated veneer lumber (LVL) produced from Beech (Fagus orientalis Lipsky) and Eucalyptus (Eucalyptus camaldulensis Dehn.) veneers. Eur J Wood Wood Prod 62(3):218–220

Blass HJ, Görlacher R (2004) Compression perpendicular to the grain. In: World conference on timber engineering, Lahti

Buchanan A (2007) Timber design guide, 3rd edn. New Zealand Timber Industry Federation, Wellington

Buchanan A, Palermo A, Carradine D, Pampanin S (2011) Post-tensioned timber frame buildings. Struct Eng 89(17):24–30

Burdurlu E, Kilic M, Ilce AC, Uzunkavak O (2007) The effects of ply organization and loading direction on bending strength and modulus of elasticity in laminated veneer lumber (LVL) obtained from beech (Fagus orientalis L.) and lombardy poplar (Populus nigra L.). Constr Build Mater 21(8):1720–1725

Carter Holt Harvey (2008) Engineering Bulletin No. 1—Strength limit states design capacity tables for CHH LVL sections. Technical report. CHH Woodproducts, New Zealand

CEN (2004a) EN 14374:2004 Timber structures—Structural laminated veneer lumber—Requirements

CEN (2004b) EN 1995-1-1:2004 Eurocode 5: Design of timber structures, Part 1-1: General—Common rules and rules for buildings +AC (2006) +A1 (2008)

CEN (2006) EN 14358:2006 Timber structures—Calculation of characteristic 5-percentile values and acceptance criteria for a sample

CEN (2010) EN 408:2010 Timber structures—Structural timber and glued laminated timber—Determination of some physical and mechanical properties

Franke S, Quenneville P (2010a) Compression strength perpendicular to the grain of New Zealand Radiata Pine lumber. Aust J Struct Eng 12(1):12

Franke S, Quenneville P (2010b) The material behaviour of radiata pine under compression. In: World conference on timber engineering, Riva del Garda

Gehri E (1997) Timber in compression perpendicular to the grain. In: International Conference of IUFRO S 5.02 Timber Engineering, Copenhagen

Hoffmeyer P, Damkilde L, Pedersen TN (2000) Structural timber and glulam in compression perpendicular to grain. Eur J Wood Wood Prod 58(1):73–80

Korin U (1990) Timber in compression perpendicular to grain. In: CIB-W18, Lisbon

Leijten AJM, Jorissen AJM (2010) Global test standards and code design rules for compressive strength perpendicular to grain. In: World conference on timber engineering, Trento

Leijten AJM, Larsen HJ, Van der Put T (2010) Structural design for compression strength perpendicular to the grain of timber beams. Constr Build Mater 24(3):252–257

Metsä Wood (2009) VTT Certificate no 184/03. Technical report. Metsä

Nelson Pine Industries Limited (2010) Nelson Pine LVL11 - NZ. Richmond, Nelson

Palermo A, Pampanin S, Buchanan AH, Newcombe MP (2005) Seismic design of multi-storey buildings using laminated veneer lumber (LVL). In: NZSEE Conference, Taupo

Shukla SR, Kamdem DP (2008) Properties of laminated veneer lumber (LVL) made with low density hardwood species: effect of the pressure duration. Eur J Wood Wood Prod 66(2):119–127

Standards New Zealand (2006a) AS/NZS 4357.2:2006 Structural laminated veneer lumber (LVL), Part 2: determination of structural properties—Test methods

Standards New Zealand (2006b) AS/NZS 4357.3:2006 Structural laminated veneer lumber (LVL), Part 3: determination of structural properties—Evaluation methods

Standards New Zealand (2010a) AS/NZS 4063.1:2010 Characterization of structural timber, Part 1: test methods

Standards New Zealand (2010b) AS/NZS 4063.2:2010 Characterization of structural timber, Part 2: determination of characteristic values

Thelandersson S, Mårtensson A (1997) Design principles for timber in compression perpendicular to grain. In: CIB-W18/30-20-1, Vancouver

Uysal B (2005) Bonding strength and dimentional stability of laminated veneer lumbers manufactured by using different adhesives after the steam test. Int J Adhes Adhes 25(5):395–403

van Beerschoten W, Palermo A, Carradine D, Sarti F, Buchanan A (2011a) Experimental investigation on the stiffness of beam-column connections in post-tensioned timber frames. In: Structural engineering world conference, Como, p 12

van Beerschoten W, Smith T, Palermo A, Pampanin S, Ponzo F (2011b) The stiffness of beam to column connections in post-tensioned timber frames. In: CIB-W18/44-7-7, Alghero

van der Put TACM (2008) Derivation of the bearing strength perpendicular to the grain of locally loaded timber blocks. Eur J Wood Prod 66(6):409–417

Wesbeam (2005) e-beam—engineered LVL beams. Technical report. Wesbeam, Perth